CATADIOPTRIC PROJECTION SYSTEMS

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D17 FIELD OF THE INVENTION

This invention pertains to catadioptric projection systems suitable for use with ultraviolet light sources and applicable to steppers and microlithography systems for the manufacture of semiconductors and liquid crystal display panels.

BACKGROUND OF THE INVENTION

Semiconductor device geometries continue to grow smaller. Because the manufacture of semiconductor devices requires the transfer of high-resolution circuit patterns be transferred to semiconductor wafers, the microlithography systems that project these circuit patterns onto semiconductor wafers must form high-resolution images.

The resolution of microlithography systems has been improved in several ways. For example, high-resolution microlithography systems use ultraviolet light instead of visible light and have high numerical aperture optical systems.

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Various types of high-resolution optical projection systems have been considered for high-resolution microlithography systems. Purely refractive projection systems are inadequate al ultraviolet wavelengths. For wavelengths below 300 nm, only a few optical materials are transmissive and refractive optical elements generally must be made of either synthetic fused quartz or. fluorite. Unfortunately, combining optical elements of synthetic fused quartz and fluorite is ineffective in eliminating chromatic aberration because the Abbe numbers of synthetic quartz and fluorite are not sufficiently different. Therefore, refractive optical systems for wavelengths less than about 300nm suffer from unacceptable levels of chromatic aberration.

Fluorite itself suffers from several disadvantages. The refractive index of fluorite changes relatively rapidly with temperature and fluorite polishes poorly. Therefore, most ultraviolet optical systems do not use fluorite, and thus exhibit uncorrected chromatic aberration.

Purely reflective projection systems avoid these difficulties, but a reflective projection system typically requires a large diameter mirror; frequently, the mirror must be aspheric. Because the manufacture of precision aspheric surfaces is extremely difficult, a reflective projection system using an aspheric mirror is prohibitively expensive.

Catadioptric projection systems have also been used. A catadioptric projection system is a projection system that uses both reflective elements (mirrors) and refractive elements (lenses). Many catadioptric projection systems for microlithography systems form at least one intermediate image within the optical system. Examples include the catadioptric projection systems of Japanese laid-open patent documents 5-25170 (1993), 63-163319 (1988), and 4-234722 (1992), and U.S. Pat. No. 4,779,966.

Japanese laid-open patent document 4-234722 (1992) and U.S. Pat. No. 4,779,966 describe catadioptric projection systems comprising a concave mirror and double-pass lens groups having negative power. In these systems, an incident light beam propagates through the double-pass lens group in a first direction, strikes the concave mirror, and then propagates as a reflected light beam through the double-pass lens group in a second direction opposite to the first direction. In these prior-art systems, the double-pass lens groups have negative power. For this reason, light incident to the concave mirror is divergent and the diameter of the concave mirror must be large.

The double-pass optical system of Japanese laid-open patent document 4-234722 (1992) is symmetric; aberrations in this optical system are extremely low, simplifying aberration correction in the subsequent refractive optical system. However, because it is symmetric, the optical system has a short working distance. In addition, because it is difficult with this system to separate the incident light beam and the reflected light beam, a beamsplitter is required. The preferable location for the beamsplitter in such a projection system is near the concave mirror. Consequently, the beamsplitter is large, heavy, and expensive.

The optical system of U.S. Pat. No. 4,779,966 comprises a concave mirror in a second imaging system. In this system, diverging light enters the concave mirror and the concave mirror must have a large diameter.

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Optical systems comprising more than one mirror can use fewer lenses than a purely refractive optical system, but other problems arise. In order to increase resolution and depth of focus, phase-shift masks are frequently used. In order to effectively use a phase-shift mask, the ratio a of the numerical aperture of the irradiation optical system and the numerical aperture of the projection system should be variable. While an adjustable aperture is easily located in the irradiation optical system, a catadioptric projection system usually has no suitable location for a corresponding aperture, adjustable or not.

In a catadioptric projection system in which a double-pass lens group is placed within a demagnifying portion of the optical system, the demagnification reduces the distance between the reflecting elements and the semiconductor wafer. This limits the number of lens elements that can be inserted in the optical path, and thus limits the numerical aperture of the projection system and the total optical power available to expose the wafer. Even if a high numerical aperture is possible, the working distance (i.e., the distance between the wafer and the most imagewise surface of the optical system) is short.

Prior-art catadioptric projection systems have optical elements arranged along more than one axis, using prisms or mirrors to fold the optical pathway. The alignment of optical elements in a system with more than one axis is expensive and difficult, especially when high resolution is required. Prior-art catadioptric projection systems are also difficult to miniaturize while simultaneously maintaining image quality. In addition, in a miniaturized prior-art catadioptric projection system, the beam-separation mirror that separates the incident light beam from the reflected light beam is likely to obstruct one of these beams.

Increasing the magnification of the intermediate image and moving the beam-separation mirror away from the optical axis have been considered as solutions to this problem. However, changing the magnification of the intermediate image requires changes to the remainder of the optical system to maintain an appropriate magnification on the wafer. This causes loss of image quality.

Moving the beam-separation mirror away from the optical axis without changing the magnification of the intermediate image can be accomplished by using light beams propagating farther off-axis and increasing the diameter of the projection system. Both of these changes are undesirable, leading to a larger, heavier projection system with less resolution.

Some prior-art catadioptric projection systems are used in full-field exposure systems in which patterns from an entire reticle are projected onto the wafer in a single exposure. Examples include the catadioptric projection systems of

Japanese laid-open patent documents 2-66510 (1990), 3-282527 (1991), and 5-72478 (1993), and U.S. Pat. No. 5,089,913. These systems have a beamsplitter (or a partially reflecting mirror) placed near a concave mirror. The beamsplitter directs light to the concave mirror and to the wafer. Because the light is divergent near the concave mirror, the beamsplitter must be large. Large beamsplitters made of prisms are expensive and difficult to manufacture; plate-type beamsplitters are difficult to keep precisely planar. Large prisms have other disadvantages, including their weight and to the difficulty of obtaining suitable raw material for their manufacture. A large beamsplitter tends to degrade image quality because of non-uniform reflectance, phase change, and absorption. For ultraviolet projection systems, a prism beamsplitter tends to have low transmittance.

In view of the foregoing, improved catadioptric projection systems for microlithography systems are needed.

SUMMARY OF THE INVENTION

This invention provides catadioptric projection systems that are readily miniaturized while maintaining image quality. A catadioptric projection system according to this invention comprises a first imaging system and a second imaging system. The first imaging system comprises a single-pass lens group and a double-pass lens group including a concave mirror. Light from an illuminated region of the reticle returns through the single-pass lens group and then enters the double-pass lens group. Light propagates through the double-pass lens group in a first direction, strikes the concave mirror, and then returns through the double-pass lens group in a second direction opposite the first direction. A turning mirror is provided between the single-pass lens group and the double-pass lens group. In some embodiments of the invention, the turning mirror directs the light from the first imaging system (after reflection by the concave mirror and back through the double-pass lens group) to the second imaging system. In alternative embodiments of the invention, the turning mirror directs light exiting the singlepass lens group to the double-pass lens group. The first imaging system forms an intermediate image of the illuminated region of the reticle near the turning mirror; the second imaging system re-images the intermediate image and forms an image of the illuminated region of the reticle on a substrate, typically a semiconductor wafer.

In such catadioptric projection systems, the diameter of the concave mirror can be kept small, the ratio of the imaging-optical-system numerical aperture and the illumination-optical-system numerical aperture σ can be variable, and an appropriate location is available for an aperture if phase-shift masks are used. In addition, such catadioptric projection systems have high numerical apertures and hence provide sufficient irradiation to the wafer as well as conveniently long working distances.

The second imaging system comprises a first lens group and a second lens group.

The single-pass lens group comprises, in order starting at the reticle, a first negative subgroup, a positive subgroup, and a second negative subgroup. Single-pass optical groups with this configuration are compact, produce high-resolution images, and permit separation of incident and reflected light beams. The magnification of the first imaging system can be selected as appropriate while still maintaining excellent optical performance. Thus, the magnification of the intermediate image can be varied. Preferably, either the first imaging system or the second imaging system demagnifies the reticle. Obtaining a demagnification using the first imaging system simplifies the second imaging system.

The first negative subgroup preferably comprises a lens with a concave surface facing the reticle. The second negative subgroup preferably comprises a lens element with a concave surface facing the double-pass lens group.

In one example embodiment, the first imaging system further comprises another turning mirror that receives light transmitted by the single-pass lens group and directs the light along an axis of the double-pass lens group. This embodiment permits the reticle and the wafer to be on substantially the same optical axis.

In another example embodiment, the second imaging system comprises further comprises a turning mirror placed between the first lens group and the second lens group. This turning mirror receives light from the first lens group and directs the light along an axis of the second lens group. This embodiment permits the reticle and wafer to be in parallel planes.

Embodiments of the invention in which the reticle and wafer are in parallel planes or are along the same axis simplify wafer exposure in scanning systems. It will be readily apparent that the invention includes other arrangements of turning mirrors.

The foregoing and other objects, features, and advantages of the invention will become more apparent from the following detailed description which proceeds with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a general schematic representation of an optical system according to the invention.

FIG. **2** shows a catadioptric projection system according to a first example embodiment of the invention.

FIG. **3** is a detailed drawing of the first example embodiment of FIG. **2** with the catadioptric projection system unfolded for simplicity.

FIG. **4** contains graphs of transverse aberrations of the optical system of the first example embodiment at various image heights.

FIG. **5** shows a catadioptric projection system according to a second example embodiment of the invention.

FIG. **6** shows a catadioptric projection system according to a third example embodiment of the invention.

FIG. **7** is a general schematic representation of a prior-art optical system.

DETAILED DESCRIPTION

For purposes of describing the invention, a "lens element" is a single lens (i.e., a single piece of "glass"); a lens "group" or "subgroup" comprises one or more lens elements. A positive lens, lens group, or subgroup has a positive focal length; a negative lens, lens group, or subgroup has a negative focal length. An "optical axis" is a straight line through centers of curvature of surfaces of optical elements. As will be apparent, an optical system can have more than one optical axis. Distances from an off-axis point to an optical axis are measured along a line through the point and perpendicular to the optical axis.

In order to describe the invention, a representation of a prior-art optical system is first described with reference to FIG. 7. A ray **102** from a location on a reticle R a distance d from an optical axis **100** is incident on a lens group A_1. The lens group A_1, comprises, in order from the reticle R and along the optical axis **100**, a positive subgroup A_{12} and a negative subgroup A_{13}. The lens group A_1 bends the ray **102**

toward the optical axis **100** so that the height b of the ray **102** as it exits the negative subgroup A_{13} is reduced. For this reason, the optical path of the ray **102** is easily blocked by a mirror M_2 placed after the negative subgroup A_{13}.

The present invention avoids this problem. With reference to FIG. **1**, a ray **202** from a location on a reticle R a distance d from an optical axis **200** is incident to a lens group A_1 comprising, in order from the reticle R, a first negative subgroup A_{11}, a positive subgroup A_{12}, and a second negative subgroup A_{13}. The first negative subgroup A_{11} bends the ray **202** away from the optical axis **200**. The positive subgroup A_{12} then bends the ray **202** towards the optical axis **200**. The height a of the ray **202** exiting the second negative subgroup A_{13} is thus increased in comparison with the prior-art system of FIG. **7**, thereby reducing the likelihood of obstruction of the ray **202** by a mirror M_2.

Because rays from the reticle R are more distant from the optical axis **200**, the lens group A_1 of FIG. **1** reduces the possibility of obstruction of rays from the reticle R by the mirror M_2. Optical systems using such lens groups can be more compact and provide enhanced image quality in comparison with prior-art optical systems.

FIG. **2** shows a first example embodiment of the invention. The first example embodiment provides a catadioptric projection system that projects a demagnified image of a circuit pattern from an illuminated region **221** (FIG. **2**(a)) of a reticle R onto a semiconductor wafer W. The illumination region **221** is illuminated by an illumination optical system, not shown in FIG. **2**. Such a projection system can project a pattern onto other substrates as well, such as a glass panel for a liquid crystal display, and it is apparent that the invention is not limited to systems for projecting circuit patterns onto semiconductor wafers. (Thus, it will be understood that "wafer" as used herein encompasses any of various appropriate substrates onto which an image, defined by the reticle R, can be projected.) In the example embodiments presented herein, the optical projection systems are intended for use at wavelengths around 193nm but it will be apparent that the invention is also applicable to other wavelengths.

The optical projection system (FIG. **2**(b)) of the first example embodiment comprises a first imaging system A that receives light from the illuminated region **221** of the reticle R and forms an intermediate image of the illuminated region. The optical projection system further comprises a turning mirror M_2 placed near the intermediate image and a second imaging system B that receives light reflected by the turning mirror M_2. The second imaging system B re-images the intermediate image onto a corresponding region **231** on the wafer W (FIG. **2**(c)).

The first imaging system A comprises a single-pass lens group A_1 and a double-pass lens group A_2. In order from the reticle R and along an optical axis **210**, the single-pass lens group A_1 comprises a first negative subgroup A_{11} comprising a negative lens with a concave surface facing toward the reticle R and a positive lens. Continuing along the optical axis **210** from the first negative subgroup A_{11}, the single-pass lens group A_1 further comprises a positive subgroup A_{12} comprising preferably a single positive lens element, and a second negative subgroup A_{13} comprising a negative lens element with a concave surface facing the double-pass lens group A_2. The second negative subgroup A_{13} is the closest of the subgroups of the single-pass lens group A_1 to the double-pass lens group A_2.

The double-pass lens group A_2 is placed along the optical axis **210** and receives light from the single-pass lens group A_1 and directs light to a concave mirror M_1 of the double-pass optical group A_2, placed on the optical axis **210**. The concave mirror M_1 reflects light back through the double-

pass lens group A_2. After passing through the double-pass lens group A_2, the light forms an image near the turning mirror M_2. The turning mirror M_2 reflects light from the first imaging system A to the second imaging system B. The turning mirror M_2 directs light propagating along the optical axis **210** to propagate along an optical axis **211** of the second imaging system.

The second imaging system B comprises, beginning near the turning mirror M_2 and proceeding along the optical axis **211**, a first lens group B_1 and a second lens group B_2. An aperture S is placed between the first lens group B_1 and the second lens group B_2.

FIG. **3** shows the optical system of the first embodiment in detail. For clarity, the folded optical path caused by the concave mirror M_1 and the turning mirror M_2 has been unfolded by inserting virtual flat mirrors immediately behind the concave mirrors M_1 and the turning mirror M_2. These virtual mirrors are not actually part of the first example embodiment but serve to simplify FIG. **3**. Such an unfolded representation of a catadioptric optical system will be readily understood by persons of ordinary skill in the art.

Table 1 contains specifications for the first example embodiment. In Table 1, the first column lists surface numbers, numbered from the reticle R to the wafer W. Surface numbers relevant to this discussion are specifically denoted in FIG. **3**. The second, third, and fourth columns of Table 1 list the radii of curvature of the optical surfaces ("r"), surface separations ("d") along the optical axis, and the lens material, respectively. The fifth column indicates the group number for each of the optical elements. Distances are in mm. Some of the surfaces of Table 1 represent plane mirrors and other planar surfaces used to simplify FIG. **3**; such surfaces do not represent actual optical elements.

Table 1 lists the elements of the double-pass lens group A_2 twice. Surfaces indicated as part of the lens group A_2 are surfaces through which pass light propagates immediately after propagating through the single-pass lens group A_1; the same surfaces through which the light propagates immediately after reflection from the concave mirror M_1 are indicated as belonging to the lens group A_2*. As will be apparent, the concave mirror M_1 is included only once.

The lenses of the first embodiment are made of synthetic fused quartz (SiO_2) and fluorite (CaF_2). Axial chromatic aberration and chromatic difference of magnification (lateral color) are corrected for a wavelength range of ±0.1 nm about a wavelength of 193 nm for use with an ultraviolet excimer laser emitting at a wavelength of 193 nm. The Abbe numbers ν_{193} given are for fluorite and synthetic fused quartz at wavelengths of 193 nm ±0.1 nm instead of the customary visible wavelengths; the refractive indices n are for a wavelength of 193 nm.

As specified in Table 1, the optical projection system of the first example embodiment provides a demagnification of the reticle R on the wafer W of ¼, a wafer-side numerical aperture of 0.6, and covers a span of 76 mm of the reticle R.

TABLE 1

(First Example Embodiment)

Lens Material Properties

Material	Index of Refraction (n)	Abbe Number ν_{193}
Fused Quartz (SiO_2)	1.56019	1780
Fluorite (CaF_2)	1.50138	2550

TABLE 1 - continued

(First Example Embodiment)

Optical System Specifications

Surf. No.	r	d	Material	Group
0	-	70.000000		R
1	-497.01528	15.000000	CaF_2	A_{11}
2	-2089.03221	0.100000		
3	4955.40172	35.000000	SiO_2	A_{11}
4	-684.52303	0.100000		
5	373.53254	40.000000	SiO_2	A_{12}
6	-458.84391	32.494228		
7	-384.75862	15.000000	SiO_2	A_{13}
8	399.06352	11.499839		
9	∞	0		
10	∞	15.000000		
11	∞	0		
12	∞	30.000000		
13	∞	0		
14	∞	15.805933		
15	360.53651	60.00000	CaF_2	A_2
16	-357.18478	1.00000		
17	-410.75622	15.00000	SiO_2	A_2
18	272.78252	3.000000		
19	264.76319	55.000000	CaF_2	A_2
20	-403.51844	8.000000		
21	-313.01237	15.000000	SiO_2	A_2
22	-536.13663	141.754498		
23	753.93969	16.200000	SiO_2	A_2
24	350.20343	24.941513		
25	502.28185	22.5000000	SiO_2	A_2
26	1917.58499	72.939269		
27	696.45818	25.920000	CaF_2	A_2
28	422.44154	45.000000		
29	-165.29930	15.000000	SiO_2	A_2
30	-247.15361	7.435035		
31	447.76970	40.000000	SiO_2	A_2
32	-650.53438	176.819005		
33	-207.03257	15.000000	SiO_2	A_2
34	3807.25755	27.000000		
35	∞	0		
36	316.26451	27.000000	(M_1)	A_2
37	-3807.25755	15.000000	SiO_2	A_2*
38	207.03257	176.819005		
39	650.53438	40.000000	SiO_2	A_2*
40	-447.76970	7.435035		
41	247.15361	15.000000	SiO_2	A_2*
42	165.29930	45.000000		
43	-422.44154	25.920000	CaF_2	A_2*
44	-696.45818	72.939269		
45	-1917.58499	22.500000	SiO_2	A_2*
46	-502.28185	24.941513		
47	-350.20343	16.20000	SiO_2	A_2*
48	-753.93969	141.754498		
49	536.13663	15.000000	SiO_2	A_2*
50	313.01237	8.000000		
51	403.51844	55.000000	CaF_2	A_2*
52	-264.76319	3.000000		
53	-272.78252	15.000000	SiO_2	A_2*
54	410.75622	1.000000		
55	357.18478	60.000000	CaF_2	A_2*
56	-360.53651	15.805933		
57	∞	0		
58	∞	30.000000		
59	∞	0		
60	∞	130.000000		M_2
61	408.08942	20.000000	SiO_2	B_1
62	203.49020	3.000000		
63	207.52684	30.000000	CaF_2	B_1
64	19354.35793	0.1000000		
65	429.85442	35.000000	SiO_2	B_1
66	-403.83438	14.478952		
67	-353.07980	15.000000	SiO_2	B_1
68	261.24968	31.363884		
69	-219.57807	23.000000	SiO_2	B_1
70	-348.23898	1.990938		
71	502.56605	40.000000	CaF_2	B_1

TABLE 1 - continued

(First Example Embodiment)

72	-747.25197	421.724019		
73	638.73572	29.16000	SiO_2	B_1
74	-809.39570	0.079197		
75	316.55680	32.805000	SiO_2	B_1
76	309.57052	15.000000		
77	-	54.627545		S
78	213.28576	51.714105	CaF_2	B_2
79	-7409.32571	13.778100		
80	-616.12401	39.000000	SiO_2	B_2
81	-1209.66082	0.373771		
82	472.08983	39.000000	SiO_2	B_2
83	1043.43948	0.267894		
84	103.01598	49.409891	SiO_2	B_2
85	77.85822	9.349712		
86	81.54405	32.465682	CaF_2	B_2
87	6656.48506	3.061800		
88	-400.35184	13.094819	SiO_2	B_2
89	-922.72813	1.399628		
90	1101.31959	16.951746	SiO_2	B_2
91	-554.93213	1.641793		
92	1392.34272	16.702978	SiO_2	B_2
93	3939.24661	15.000000		
94	∞			W

FIG. 4 provides graphs of transverse aberrations of the first example embodiment for several values of image height Y at three wavelengths. As is apparent from FIG. 4, the transverse aberrations are well-corrected even at the full numerical aperture.

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In the first example embodiment, the optical projection system does not project the entire reticle R onto the wafer W in a single exposure. Rather, as shown in FIG. 2(a), an illuminated region **221** of the reticle R is projected onto a corresponding exposure region **231** on the wafer W (FIG. 2(c)). In the first embodiment, the illuminated region **221** is rectangular, 120 mm long and 24 mm wide. The length of the illuminated region **221** is symmetrically placed with respect to a line **222** perpendicular to the optical axis **210**.

The width of the illuminated region **221** is such that the illuminated region **221** extends from 52 mm to 76 mm from a line **223** perpendicular to the optical axis **210**.

The pattern from the entire reticle R is transferred to the wafer W by synchronously scanning both the reticle R and the wafer W during exposure of the wafer W. Arrows **241, 242** indicate the scan directions for the reticle R and the wafer W, respectively. It will be apparent that other shapes and sizes of the illuminated region can be used.

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In the first example embodiment, the turning mirror M_2 so receives light reflected by the concave mirror M_1 and directs the light to the second imaging system B. The invention also provides an alternative arrangement in which the turning mirror M_2 receives light from the single-pass lens group and directs the light to the double-pass lens group and the concave mirror M_1. Light reflected by the concave mirror M_2 then propagates directly to the second imaging system without reflection by the turning mirror M_1. In the first example embodiment and in such a modification of the first example embodiment, the fuming mirror M_1 thus separates light propagating from the double-pass optical group A_2 and light propagating to the double-pass optical group A_2.

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A second example embodiment of the invention is shown in FIG. **5**. The optical projection system of FIG. **5** is similar to that of the embodiment of FIG. **2**. Light from an illuminated region **321** (FIG. 3(a)) of a reticle R is directed to, beginning nearest the reticle R and along an optical axis **310**, a single-pass lens group A_1 comprising a first negative subgroup A_{11}, a positive subgroup A_{12}

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and a second negative subgroup A_{13}. After the second negative subgroup A_{13}, a turning mirror MO reflects the light along an optical axis **311** of a double-pass lens group A_2 including a concave mirror MI. Light is transmitted by the double-pass lens group A_2 and is reflected by the concave mirror M_1 back through the double-pass lens group A_2 to a turning mirror M_2. An intermediate image of the illuminated region **321** is formed near the turning mirror M_2.

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The turning mirror M_2 directs the light from the illumi-nated region of the reticle R along the optical axis **310** which is an optical axis of the second imaging system B as well as of the single-pass lens group A_1. The second imaging system B receives light from the turning mirror M_2 and re-images the intermediate image onto a corresponding region **331** on the wafer W. As will be apparent, the second embodiment differs from the first embodiment in that the turning mirror M_0 is placed between the single-pass lens group A_1 and the double-pass lens group A_2. The turning mirror M_0 permits the reticle R and the wafer W to be in parallel planes. As shown in FIG. **5**, the reticle R and the wafer W are along the same optical axis 312.

With reference to FIG. **6**, an optical system according to a third example embodiment of the invention differs from the first embodiment in that a turning mirror M_3 is placed between the first lens group B_1 and the second lens group B_2 of the second imaging system B. As a result of the reflection by the turning mirror M_3, the optical system of the third example embodiment transfers a pattern from an illuminated region **421** of the reticle R (FIG. **6**(a)) to the wafer W wherein the reticle R and the wafer W are in parallel planes. Unlike the second example embodiment, the wafer W and the reticle R of the third example embodiment are on separate optical axes **401, 402** of the first imaging system A and the second lens group B_2 of the second imaging system B, respectively.

In the third example embodiment, the turning mirror M_2 receives light reflected by the concave mirror M_1 and directs the light to the second imaging system B. The invention also provides an alternative arrangement in which the turning mirror M_2 receives light from the single-pass lens group and directs the light to the double-pass lens group and the concave mirror M_1. Light reflected by the concave mirror M_2 then propagates directly to the second imaging system without reflection by the turning mirror M_1.

The first, second, and third example embodiments are similar to each other, but differing in respect to the number and placement of turning mirrors. Therefore, these example embodiments provide the same image quality.

In each of the example embodiments described above, the single-pass lens group A_1 comprises a first negative subgroup, a positive subgroup, and a second negative subgroup. The catadioptric projection systems of this invention are readily miniaturized with no loss of image quality. While FIGS. **2**, **5**, and **6** show a scanning exposure of the wafer W, the catadioptric projection systems of this invention can also be used for full-field exposure.

The catadioptric projection systems of the present invention include several other favorable characteristics. First, a turning mirror (or a beamsplitter) can be placed near the intermediate image, thereby reducing the size of the turning mirror. Second, unlike conventional catadioptric projection systems that allow light reflected by a mirror to overlap with the incident light (which makes placement of the aperture S difficult), the catadioptric projection systems of the present invention allow the aperture S to be placed in the second